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Duct Leakage Repeatability Testing

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DISCLAIMER

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INTRODUCTION

Duct leakage often needs to be measured to demonstrate compliance with requirements or to determine energy or Indoor Air Quality (IAQ) impacts. Testing is often done using standards such as ASTM E1554 (ASTM 2013) or California Title 24 (California Energy Commission 2013 & 2013b), but there are several choices of methods available within the accepted standards.

Determining which method to use or not use requires an evaluation of those methods in the context of the particular needs. Three factors that are important considerations are the cost of the measurement, the accuracy of the measurement and the repeatability of the measurement. The purpose of this report is to evaluate the repeatability of the three most significant measurement techniques using data from the literature and recently obtained field data. We will also briefly discuss the first two factors. The main question to be answered by this study is to determine if differences in the repeatability of these tests methods is sufficient to indicate that any of these methods is so poor that it should be excluded from consideration as an allowed procedure in codes and standards.

The three duct leak measurement methods assessed in this report are the two duct pressurization methods that are commonly used by many practitioners and the DeltaQ technique. These are methods B, C and A, respectively of the ASTM E1554 standard. Although it would be useful to evaluate other duct leak test methods, this study focused on those test methods that are commonly used and are required in various test standards, such as BPI (2010), RESNET (2014), ASHRAE 62.2 (2013), California Title 24 (CEC 2012), DOE Weatherization and many other energy efficiency programs.

Repeatability is considered important by some practitioners who are concerned about differences between two tests on the same home, for example as part of a quality control procedure. Repeatability is also an indication of the resolution of the test method that becomes more important for tight duct systems. The results of this study can be used by organizations such as RESNET (in home performance ratings), ASHRAE (for standard 62.2 and possibly 90.2) and other building codes and standards in determining what tests are appropriate for their specific application.

BACKGROUND

Until now there has been little investigation of the repeatability of either of the pressurization test methods. There has been some study of repeatability for DeltaQ testing and the current study will add to this existing body of knowledge. The repeatability of the three tests will be determined by performing the tests multiple times in homes. Previous studies have only done a few tests in each home. In order to better estimate repeatability and hopefully capture a wider range of weather conditions at each home, this study planned for a whole day of testing with a target of ten repeat tests in each home performed throughout the day. Ten homes were tested in each of three geographical locations to capture a range of home and duct system design and construction. The initial plan was to only test tight duct systems[1] because we want to evaluate the tests under the conditions that they are most used for - i.e., to confirm low leakage. However, as the results showed, there was a large range in duct leakage among the tested homes. Another requirement was that the homes have at least part of their duct system outside the conditioned space of the home. The overall intent is to produce a dataset that robustly evaluated the repeatability of the three test methods so that we could draw conclusions about test applicability and possible repeatability associated limitations.

Measurement Techniques

Different measurement methods have been developed to determine different aspects of duct leakage. The three key aspects include the following:

1. Total leakage ***or*** leakage to outside only. When considering energy issues or impacts on home ventilation only the leakage to outside is of interest. Total leakage may be used for quality control for tight ducts (particularly if testing is performed during construction and the building envelope is incomplete).

2. Separation of supply and return leaks. Supply and return leaks have different impacts on the thermal losses of distribution systems. The imbalance between supply and return also impacts ventilation and home pressures. Balanced supply and return leaks combine linearly with natural infiltration, while the imbalanced portion combine in a sub-additive, non-linear fashion. Excess return leakage has been observed as a culprit in homes that experience excessive depressurization and resulting combustion appliance backdrafting.

3. Leakage under normal operating conditions or at a fixed pressure. For energy calculations or estimating impacts of ventilation and home pressures the actual leakage flows at normal operating conditions are needed. Generally, it is not possible to determine the pressures across each leak in the duct system that would allow conversion from fixed pressure testing to operating conditions. Fixed pressure testing can still be effective if the target leakage levels are very low and the conversion from test pressures to operating pressures does not change the magnitude of the flow significantly.

There are, accordingly, three variations of pressurization tests that deal with these aspects.

1. For total leakage only the ducts are pressurized. For leakage to outside both the ducts and house are pressurized simultaneously.

2. If the supply and return are physically separated by installing a barrier inside the system (normally in the blower compartment) then the supply and return can be tested separately. Otherwise the whole duct system leakage is reported as a single number.

3. The pressurization is performed at a single fixed pressure (usually 25 Pa). Because the actual pressure across the duct leaks depends on the location of the leak in the system and individual duct system pressures, some test methods attempt to correct to system pressures by measuring the pressures in the system and making simplifying assumptions about leak location.

In practice, most applications of pressurization ignore aspects 2 and 3, resulting in two options for pressurization testing: total leakage and leakage to outside. For both tests, a duct leakage tester is

[1] A tight duct system is one that would meet the 6% of total system flow requirement that is used in several codes and standards. For example, ASHRAE 62.2-2013 and California Title 24-2013 (California Energy Commission (2012)

attached to the duct system and the registers are sealed. For total leakage, the flow required to pressurize the ducts to 25Pa is recorded. For leakage to outside a blower door is used to pressurize the house to the same pressure as the ducts (25 Pa).

One alternative to pressurization is called DeltaQ and it measures leakage to outside at operating conditions and also separates supply and return leaks. DeltaQ testing uses a blower door mounted in a door connecting inside to outside. Four tests are conducted combining depressurization, pressurization and with the HVAC system blower off and on. A computer is used to analyze the data and calculate the duct leakage to outside at operating conditions.

ASTM E1554 describes how to perform all three test methods. Other entities include step-by-step procedures for the two pressurization tests that differ only in detail from the ASTM standard. Some test equipment manufacturers have developed hardware and software that automates some of the testing procedures: they include automatic time averaging of pressures and air flows, automatic fan control to maintain fixed pressures (particularly useful for duct pressurization testing) and complete automation of fan operation, pressure measurement and data analysis for DeltaQ testing.

Previous Repeatability Studies

For DeltaQ testing, several previous studies have examined repeatability. Walker and Dickerhoff (2006) performed the DeltaQ test five times in each of three homes. The root mean square of the variability for supply and return leakage in the three homes ranged from 5 to 7 cfm and scaled with envelope leakage. A rough rule of thumb was proposed to estimate repeatability uncertainty as 1% of the envelope air leakage at 50 Pa (Q50). Walker and Dickerhoff (2008) added repeatability test results from another home in Madison, WI during which the furnace blower was not turned on[2]. An additional seven homes were tested for DeltaQ repeatability by Dickerhoff and Walker (2008). All these homes roughly conformed to the 1% Q50 rule of thumb.

Francisco et al. (2003) tested ten homes twice and we can use the difference between the two tests as a very basic repeatability uncertainty. Two homes had extreme differences, five times bigger than the other tests (of about 250 cfm), and it is unclear why the differences were so large in these homes but not in others. Figure 1 includes all these data (21 homes total) with the exception of the two outliers to illustrate the trend of increasing DeltaQ test repeatability uncertainty with envelope leakage. The solid line in the figure represents an estimate of repeatability uncertainty using 1% of Q50. A least squares fit to the data results in uncertainty increasing slightly faster with Q50 at 1.076%, however, given the variability in the test results this 7.6% difference is not significant and is ignored for simplicity. The mean and RMS error between the rule of thumb and the actual RMS differences <1 cfm and 10 cfm (<0.5 L/s and 5 L/s), respectively. The RMS difference is reduced to 8 cfm (4 L/s) by removing the one high outlier). Note that the 1% Q50 uncertainty estimate is for supply and return leaks individually. For total duct leakage this uncertainty estimate would be increased (we cannot just double it because, by the nature of the DeltaQ test calculations, the uncertainties in supply and return leaks are not independent).

[2] Although this is not strictly a DeltaQ test, we include it here for completeness.

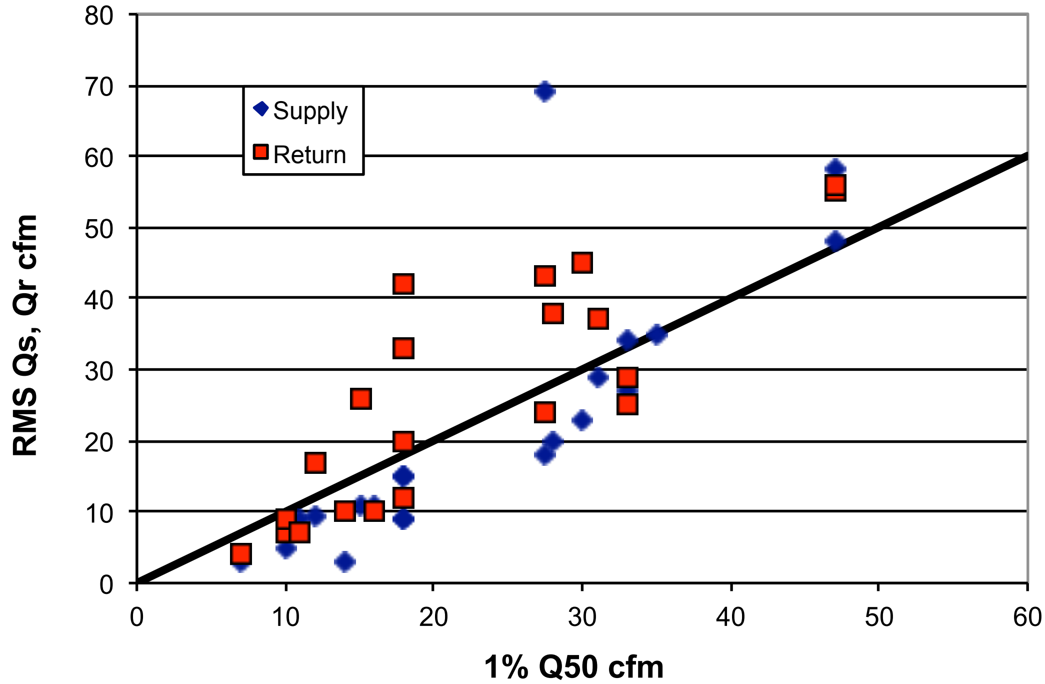

Figure 1. RMS repeatability uncertainties for DeltaQ testing in 21 homes compared to 1%Q50 (solid line).

For fan pressurization studies, Walker et al. (1998) tested nine new homes in southern California with predominantly attic ducts using pressurization testing. The tests were repeated two to four times - with most homes tested three times. The repeatability uncertainties averaged 16 cfm (3% of measured leakage flow - these were very leaky duct systems). Two of the tests in each home were by the same test crew on different days. The differences between the tests by the same crew were lower - averaging 11 cfm.

The current study aims to add to these previous results in which repeatability was not a focus and the number of repeats of each test were generally low (in the 2 to 5 range). The field tests in this study aimed for ten repeats of each test to provide better defined estimates of repeatability uncertainty.

FIELD TESTING

New field data of repeatability was generated for the purposes of this study by three different Building America teams, each in a different location:

1. In the Champaign, IL area by PARR.

2. in the Minneapolis, MN area by CEE.

3. In the Atlanta, GA area by Southface.

Ten homes were tested in each location. At each test house roughly a day was spent performing each test. As many tests as possible were performed each day - typically seven to ten test repeats were achieved. Tests were performed from early morning through the afternoon in an attempt to capture a range of weather conditions in terms of temperature differences and wind speeds that are often diurnal.

The measurement protocol and the detailed data are included in Appendix A. In addition to the duct leakage flows, house and duct system characteristics were recorded as well as ambient wind and temperature conditions. The furnace blower flow was recorded in order to normalize the leakage flows. This normalized metric is useful because many code and standard duct leakage requirements are expressed as a fraction of the total system air flow (typical new duct system requirements limit duct leakage to 6% of blower flow). The time to perform each test was also recorded.

RESULTS

The results are presented by location and for all tests combined and as an absolute flow in cubic feet per minute (cfm) and as a fraction of blower flow (%). For each home the average (avg.) and standard deviation (s.d.) of the duct leakage were determined. In the following tables the following abbreviations were used:

"Press" is for pressurization total leakage at 25 Pa

"Pout" is for pressurization leakage to outside at 25 Pa

"DQs" is for DeltaQ supply leakage

"DQr" is for DeltaQ return leakage

House and System Summary Characteristics

Table 1 shows that these homes were typical of existing homes in the US with an average leakage of 1939 cfm at 50 Pa (corresponding to about 7.5 ACH50 (Air Changes Per Hour at 50 Pa) or Normalized Leakage[3] (NL) of 0.6[4]). There was little variation in average envelope leakage between the three test geographical locations but large variation from home to home with a standard deviation in envelope leakage of about +/- 50% and a wide range from minimum to maximum. This wide range is good for the purposes of this study because it ensures that the tests are exercised over a wide range of envelope leakage. The average blower flow varied by about 20% from region to region and also had significant house to house variability. There was a large range of house size from 800 ft^2 to 3450 ft^2 with an average of 1829 ft^2. For the PARR and Southface tests the wind speeds were low - typically 1 to 2 mph but the CEE tests reported much higher wind speeds of about 10 mph. Previous work by Dickerhoff and Walker (2008b) showed that there was no trend in increased or decreased DeltaQ test results with increasing wind speed. However, they also showed that the DeltaQ sensitivity to wind is predominantly from short

[3] Normalized leakage is defined as $NL = 1000 \cdot \frac{ELA}{A_{floor}} \cdot \left[\frac{H}{Hr}\right]^{0.4}$ where ELA is the effective leakage area of the house from an envelope air leakage test (m^2 or ft^2), A_{floor} is the house floor area (m^2 or ft^2), H is the eave height of the home and H_r (m or ft) is the reference eave height (2.5 m or 8.2 ft).

[4] Chan and Sherman (2013) gave a geometric mean NL=0.61 for air leakage tests of 134,000 US homes

term gusts that disrupt only part of the test and this may not be reflected in single point or average wind speeds for a test.

Table 1. House and System Characteristics										
	Envelope Leakage, Q50 (cfm)				Blower Flow (cfm)					
	Average	s.d.	Min.	Max.	Average	s.d.	Min.	Max.	Floor Area (sq.ft.)	Wind speed (mph)
PARR	2002	921	940	3445	1030	771	380	2942	1364	2
CEE	1936	587	945	2911	891	205	704	1424	2465	10
Southface	2879	1181	1219	4456	706	281	296	1128	1658	1
All	**2272**	**1022**	**940**	**4456**	**876**	**490**	**296**	**2942**	**1829**	**4**
	Envelope Leakage, ACH50									
	Average	s.d.	Min.	Max.						
PARR	12.3	6.1	4.2	21						
CEE	6.2	2.1	3.6	10.9						
Southface	14.1	5.8	8.1	23.9						
All	**11**	**6**	**3.6**	**23.9**						

Duct Leakage

For the pressurization tests the result is the combination of supply and return leaks. Because the DeltaQ test separates supply and return leakage the DeltaQ test results will be presented as both supply and return separately and also with the supply and return combined for a total that can be compared to the other tests. In some cases of pressurization testing the ducts were so leaky that the air flow required to get to 25 Pa exceeded the capacity of the test equipment. For these ducts that were not fully pressurized to 25Pa the results were extrapolated to 25Pa assuming a pressure exponent of 0.5. This will introduce additional uncertainties due to assuming a fixed pressure exponent that may not be true for all or some of the leaks. In addition, field experience and the physics of air flow in the ducts indicate that it is difficult to achieve uniform test pressures when leakage is this high meaning that not all the duct leaks experienced the same test pressure. Without additional pressure measurement points and some prior knowledge of air leakage locations it is difficult to estimate the additional uncertainty resulting from this non-uniformity of pressures. However, it is fair to point out that at these very high leakage levels decisions about duct repair or passing or failing a leakage criterion will not change if the additional uncertainties are accounted for.

The results in Tables 2 and 3 (and Figure 2) show that the PARR and Southface homes had quite leaky ducts, with tight ducts occurring in the CEE results. This is important because some applications for duct leakage testing are specifically for tight ducts and we will focus on those results for that application later in the discussion. The results show that generally the test with the lowest repeatability uncertainty is the pressurization testing to outside with an overall uncertainty of about 12 cfm or 1% of blower flow. The pressurization and DeltaQ repeatability results are very close at about 40 cfm and 6% of blower flow.

Table 2. Duct Leakage results, cfm

	DeltaQ avg.	DeltaQ s.d.	Press avg.	Press s.d.	Pout avg.	Pout s.d.	DQs avg.	DQs s.d.	DQr avg.	DQr s.d.
PARR	190	32	666	30	492	18	107	14	82	21
CEE	39	36	1001	8	87	2	16	16	24	21
Southface	220	46	1075	92	442	15	95	21	126	26
All	**150**	**38**	**914**	**43**	**340**	**12**	**73**	**17**	**77**	**23**

Table 3. Duct Leakage results, fraction of blower flow, %

	DeltaQ avg.	DeltaQ s.d.	Press avg.	Press s.d.	Pout avg.	Pout s.d.	DQs avg.	DQs s.d.	DQr avg.	DQr s.d.
PARR	21	3	72	3	56	2	12	2	9	2
CEE	4	4	110	1	9	0	2	2	3	2
Southface	43	10	181	15	80	2	19	4	26	5
All	**23**	**6**	**121**	**6**	**48**	**1**	**11**	**3**	**13**	**3**

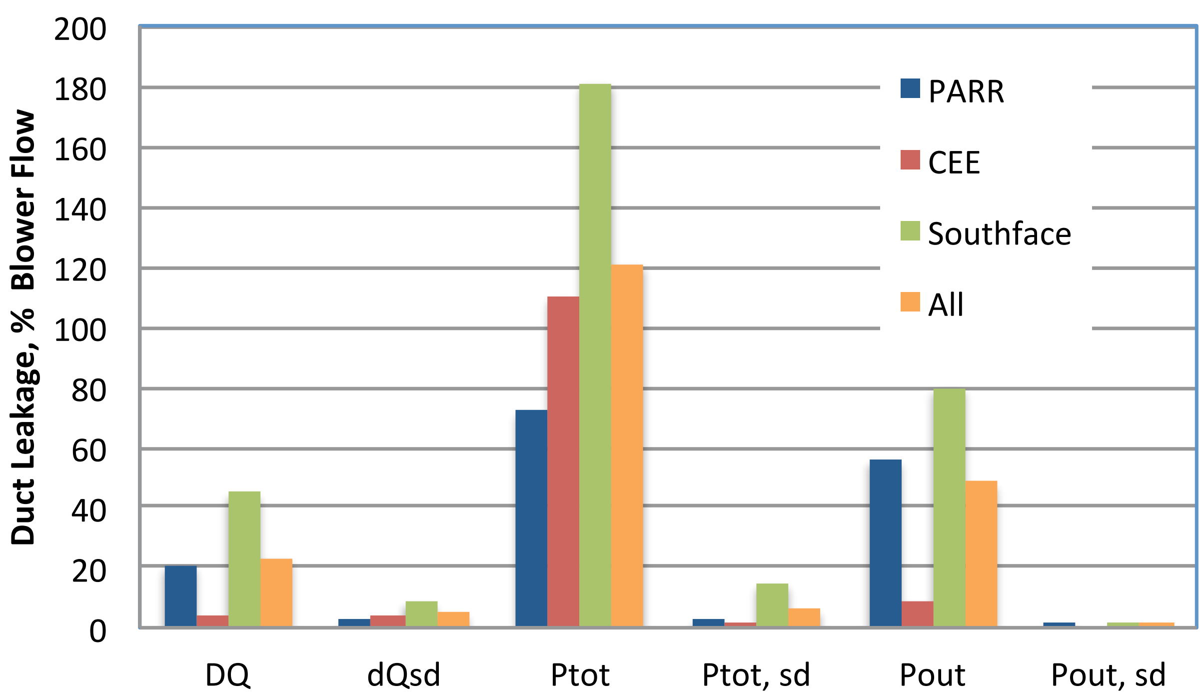

Figure 2. Comparison of average and standard deviations of duct leakage flows for the three separate study groups and all groups together.

Low Leakage Results

An initial goal of this study was to focus on low leakage ducts. This was because key applications for these test methods are those that are testing low leakage ducts – typically to a criterion of less than 6% of blower flow (as used in ASHRAE 62.2, California Title 24-2013 (California Energy Commission (2012))). For the pressurization test results, no duct systems met this 6% limit. For the pressurization to outside test results, five systems met this limit. For four out of five homes the DeltaQ results were also less than 6% - showing some agreement between these two approaches as a screening for tight ducts. However, the DeltaQ results were less than 6% in 12 homes and in only four of these were the pressurization to outside test results less than 6%.

For the 12 homes with DeltaQ test results less than 6% of blower flow Tables 4 summarizes the test results.

Table 4. Low Leakage (<6%) Duct Leakage results						
	DeltaQ avg.	DeltaQ s.d.	Press avg.	Press s.d.	Pout avg.	Pout s.d.
cfm	**29**	**28**	**832**	**10**	**115**	**3**
% blower flow	**3**	**3**	**91**	**1**	**14**	**0.3**

Other testing issues

In addition to repeatability, there are other aspects to duct testing reliability that need to be considered. In some homes the ducts were so leaky that they could not be pressurized to 25 Pa or pressurization testing produced leakage flows greater than the total blower flow. Both of these test results are problematic and lead to very misleading results. It appears that the pressurization to outside test results are more reasonable - but are likely still too high at almost half of blower flow on average. Seven of the thirty homes had systems that could not be pressurized to 25 Pa and one home where pressurizing to outside also could not reach 25 Pa. Eighteen of the 30 homes had pressurization leakage greater than the blower flow. These results significantly limit the applicability of these pressurization tests. When testing duct systems that exhibit such high leakage levels it is best to avoid pressurization testing. It would be convenient if house or duct system characteristics could be observed before testing is started that would allow a practitioner to identify systems that would exhibit these types of results and so choose an alternate test method (such as DeltaQ). Based on observations from this study and other anecdotes from practitioners, it appears that basement duct systems often exhibit these artificially high leakage levels from pressurization testing. Another option is to make an attempt to seal systems before testing that clearly have visible leaks. This could include eliminating building cavities used as HVAC air flow paths by installing ducting, reconnecting disconnected ducts and sealing large holes and visually obvious leaks.

For DeltaQ testing, there are also occasional unrealistic results. For DeltaQ the results were occasionally negative. This occurs when the duct leakage is low and the uncertainty results in a negative leakage being reported. There were two occurrences of negative supply leakage and two of negative return. In one home these combined to give a negative total - albeit only 1 cfm. Although the DeltaQ test has fewer issues than pressurization testing in this study, it is important to note that other studies have occasionally shown anomalous DeltaQ results. For example, as discussed earlier, Francisco et al. (2003) had DeltaQ test results that varied greatly between two tests by about 250 cfm. Dickerhoff and Walker (2008) showed that large DeltaQ errors were usually the result of wind gusts during testing and that repeating the part of the test with the wind gust could reduce these problematic test results. The important issue is that, although DeltaQ testing showed far fewer anomalous test results in the current study, all three test methods are susceptible to producing nonsensical results. For DeltaQ testing problematic parts of the test can be repeated to reduce these problems. For pressurization testing it is likely that for some duct systems and installations the test approach simply fails. Based on the results of this study basement ducts are most likely to have this problem (10 out of 12 homes), followed by crawlspace ducts (6 out of 11 homes)[5]. Homes with attic ducts did not exhibit this problem. This is likely due to differences in installation practices between duct locations. For example the use of panned joists and wall cavities is more common for ducting in basements (and, to a lesser extent, crawlspaces) and would be very rare in an attic-based system.

The tests that include an envelope pressure measurement: DeltaQ and pressurization to outside, might be expected to show greater sensitivity to wind speed fluctuations that change the envelope pressures during the test. However, the results show that the much higher wind speeds reported by CEE did not result in higher test variability for either test procedure. This agrees with the discussion and analysis in Dickerhoff and Walker (2008) who also found that increased wind speed itself was not necessarily an indicator of increasing DeltaQ errors, rather it is the presence of sustain gusts over several seconds (i.e., changing windspeeds) during the measurements that can lead to large errors. It is possible that the averaging techniques for measuring pressures and the automated test and control procedures for DeltaQ are good at counteracting wind-induced pressure fluctuations. It should be noted that the CEE and Southface windspeed measurements were not measured directly on site but were taken from nearby weather stations and it is possible that the wind experienced by the home may be different from that recorded for the test.

Figure 3 illustrates the variability in supply and return leakage from the DeltaQ test as a function of envelope leakage in a similar way to Figure 1, in order to examine the plausibility of using 1% of Q50 as a rule of thumb for estimating the leakage uncertainty. The figure also includes linear least squares fits to the data that indicate the 1% rule of thumb works on average for the return leakage but may overestimate repeatability uncertainty for the supply leakage.

Figure 4 combines the results in Figures 1 and 3. The linear least square fit to all the data shows that 1% of Q50 is a reasonable rule of thumb to use for DeltaQ repeatability uncertainty.

[5] Note that duct location information was not available for all homes, so the total number of homes does not add up to 30. Also, some homes had ducts in multiple locations, in which case ducts were classified as being in both locations for this breakout of pressurization issues.

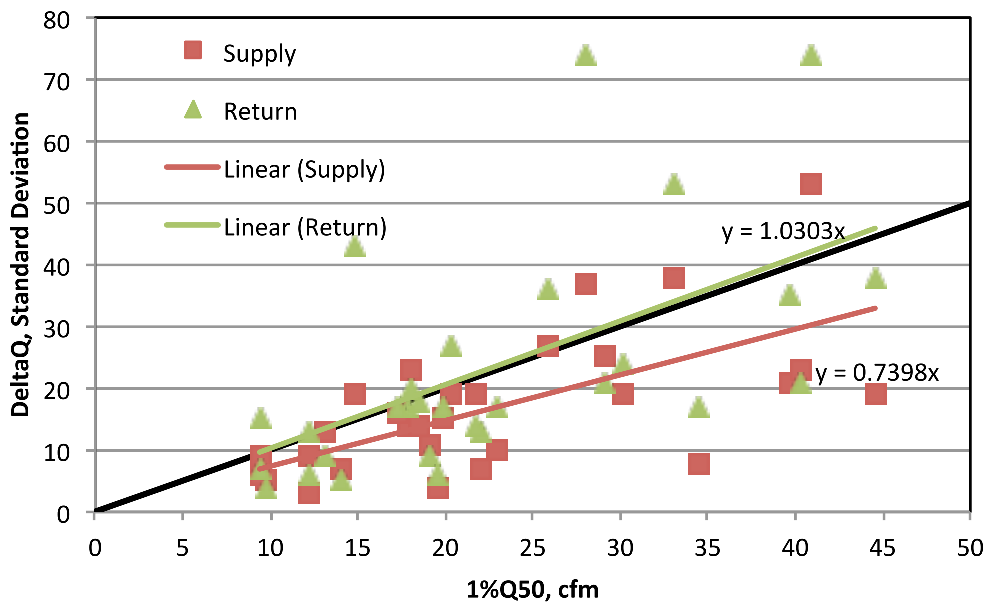

Figure 3. Repeatability uncertainties for DeltaQ testing compared to 1%Q50 (solid line).

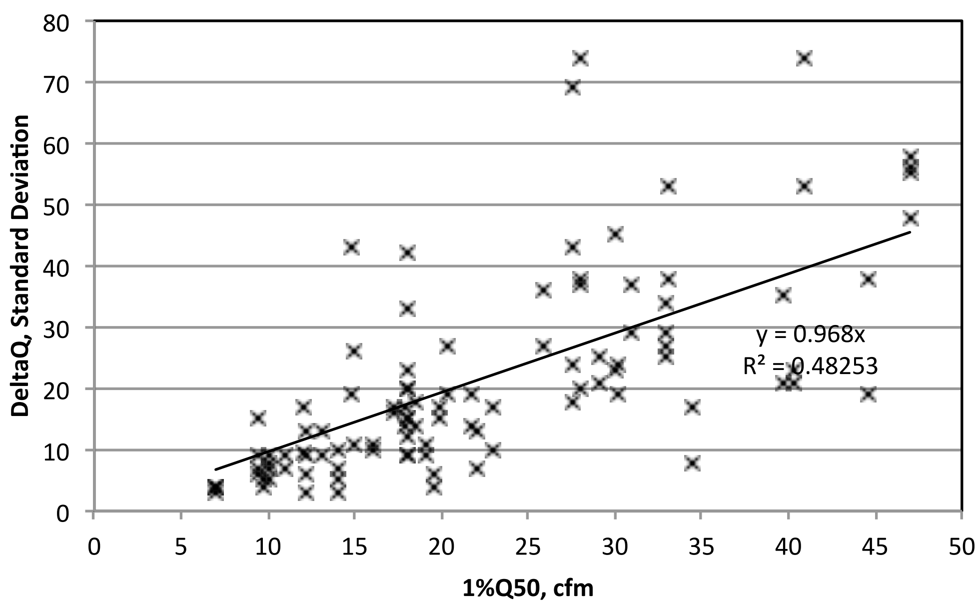

Figure 4. Repeatability uncertainties for DeltaQ testing compared to 1%Q50 combining test results from the current study with previous studies.

Time to Perform the Tests

When analyzing the time required to perform the tests, one result was immediately obvious: the first test in each home took much longer than subsequent tests. This is due to one-time setup tasks that were required for the first test, but not subsequent tests. For all the tests, this includes unpacking and setting up the equipment, finding/turning off the water heater, locating the thermostat, setting up and connecting the manometer/duct leakage tester/blower door controller, launching computer software, making sure all windows and doors are appropriately open or closed, ensuring exhaust devices are deactivated, locating all registers, and consulting homeowners (if present) on what is happening and what is needed from them. For the test equipment, some of the set up tasks are also one time only, such as laying out hoses and electronics/power/communication cables. For DeltaQ testing additional time was required to turn on the computer and control software. For pressurization testing initial time was required to create templates to connect the duct leakage tester to the duct system.

Between subsequent tests duct leakage tester were removed and reinstalled, blower doors removed and reinstalled. For DeltaQ testing, additional time was needed if issues arose during the test, such as a strong gust of wind, a pinched hose, a homeowner exiting/entering the house, a manometer hose incorrectly setup for pressurization, blower fan left on (or off) during testing. For pressurization testing subsequent tests required resealing of all the registers.

In any real testing environment, testers will only test the house a single time. Therefore the first test time results are more indicative of what testers would experience in practice.

Table 5 summarizes the time taken to perform the tests split into the first test and subsequent tests. The first test generally took double the time of subsequent tests - roughly thirty minutes longer. The DeltaQ test is the fastest on average for the first test by about 10 to 15 minutes with the average for the two pressurization tests only three minutes different. The variability in time to perform tests for all three procedures was about the same for the first test - about 20 minutes. This variability indicates that some houses are easier to set up than others. This is reinforced by the variability in time required to do the tests also being significantly reduced after the first test dropping from 20 minutes for the first test to only 3 minutes variability for subsequent tests.

Table 5. Time taken to perform each test, minutes

	DQ, first avg.	DQ, first s.d.	DQ avg.	DQ s.d.	Press, first avg.	Press, first s.d.	Press avg.	Press s.d.	Pout, first	Pout, first s.d.	Pout avg.	Pout s.d.
PARR	54	15	31	4	60	27	27	13	63	24	26	13
CEE	53	24	19	2	76	15	34	6	67	17	38	4
ALL	**54**	**20**	**25**	**3**	**68**	**21**	**31**	**10**	**65**	**21**	**32**	**9**

One interesting result of the times in Table 5 is that the pressurization to outside appears to take less time than the total system leakage test. This is unexpected because it requires the same duct system set-up as the total system test with additional time required to set up and operate the blower door. It is potentially explained by the fact that that the total system test was done before the test to outside in the protocol used and thus bore all the learning curve associated with sealing registers. Some field testing teams reported that all the equipment (including the blower door) was set up at the house before testing started and the total and to outside pressurization test were performed back-to-back. This makes it harder to disaggregate this extra time. Field test teams also report that a total test may take longer in very leaky-to-inside systems requiring more checking and rechecking of taping and hoses to make sure that the result is reasonable. With the leakage-to-outside tests it is more likely to get a result that is immediately believable.

DISCUSSION

Repeatability

In terms of repeatability of the test results, the data clearly shows that the pressurization to outdoors tests are the most repeatable with a standard deviation of only 1% of the blower flow. The other two methods are approximately 6%. If repeatability were the only criterion this result would suggest that that should be the only method used. This method, however, is the costliest because it requires the most equipment (both blower door and duct blaster) and the most time in the field.

The other two methods provide roughly the same repeatability at 6% of blower flow. The DeltaQ technique separates out supply and return leakage at 3% error each, which is of interest if separate supply and return leakage estimates are required, e.g., for better targeting of particular parts of the duct system for sealing.

Looking at tighter duct systems only (DeltaQ <6% of blower flow), the repeatability improves for all the test methods. Pressurization to outside has the lowest average standard deviation of 0.3%, with pressurization improved to 1%. The DeltaQ test showed the least improvement for the tight duct subset with a standard deviation of 3%. It should be noted that even for these low leak tests the indicated leakage flows varied considerably. The DeltaQ test results averaged 30 cfm, the pressurization to outside tests averaged 115 cfm and the pressurization test results were still unbelievably high at 800 cfm.

Based on repeatability alone we cannot conclude that any method to too poor to use. Looking to the future and applying these test methods to high performance homes, these repeatability uncertainty estimates could be improved by testing more homes with tighter envelopes and duct systems because for this data set the majority of homes had very poorly sealed systems.

Bias and Accuracy

The discussion above ignores the fact that each of the methods is measuring a different quantity. Since they are, it is important to address how well the quantity that is measured meets the needs of those who are requiring the test and how much extra uncertainty is associated with turning what is measured into what is needed.

There are typically two schools of thought. If one is going to use the value as part of some estimation of energy or indoor air quality, then it is normally clear what the parameter is. Energy and airflow models, for example, usually need to know the supply and return leakage at operating condition to estimate duct leakage impacts. In this case test methods that measure leakage at a fixed pressure have an additional uncertainty because of the need to extrapolate to the desired quantity.

In order to provide more context for these uncertainties, we need to compare the total uncertainty of DeltaQ and pressurization testing. Because pressurization testing measures an air flow at a fixed pressure, the air flow at operating conditions may not be the same as the tested air flow. This issue of not having the same pressure across the leaks during the duct pressurization test as during normal operation is a bigger source of uncertainty than repeatability. Several studies have been performed where the true leakage was known: a laboratory study by Walker and Dickerhoff (2008) has shown duct pressurization errors (40 to 60 cfm) that were double those of DeltaQ testing (20 to 30 cfm). An earlier laboratory study by Andrews (2002) also showed that pressurization errors were double those for DeltaQ testing. Francisco et al. (2003) reported similar differences of a factor of two increase in uncertainty for pressurization compared to DeltaQ in a field study of 51 homes.

The second school of thought is that a requirement is set at some stringent level and the leakage test is more of a pass-fail than a quantitative measurement. In such a case, larger biases can be tolerated because the energy or IAQ impact of those biases would be small, but there may be cost or repeatability benefits of other methods. It is then reasonable to ask the question of whether a test method might be sufficiently poor in low-leakage cases as to be precluded. At the current state of the art, 6% of blower flow is what is generally considered the boundary of low-leakage.

The results of this study showed that at the 6% limit the pressurization to outside and DeltaQ tests agreed on four out of five homes for homes where the pressurization results were less than 6%. However, the DeltaQ test identified an additional 8 homes where there was less than 6% leakage. These results suggest that if a home were to pass the screening test using pressurization to outside it is likely to also pass using the DeltaQ test. The DeltaQ test will show that more homes pass than using pressurization to outside.

These results are very close to previous comparisons of DeltaQ and pressurization to outside testing in Walker et al. (2001). Using the same 6% leakage limit the two tests agreed in 76 of 88 homes tested, and DeltaQ testing passed more homes (11) than pressurization to outside (5). None of the homes passed the duct pressurization to outside test but failed DeltaQ.

The results presented in Francisco et al. (2003) show similar results, but were for supply leakage only and total pressurization, not pressurization to outside. Francisco compared both tests to a reference technique. Eight houses had duct leakage less than 6% of blower flow. DeltaQ correctly identified seven of these tests. DeltaQ also identified one house as having excess leakage (11% instead of 6%) and two houses as having less than 6% leakage when their baseline reference leakage was 7% and 10%. For fan pressurization, only two of the eight houses with leakage less than 6% were correctly identified. Therefore, six houses were incorrectly identified as being too leaky. In addition, pressurization identified one house with less than 6% leakage when the baseline reference indicated 10% leakage. These results indicate that DeltaQ is at least as good as pressurization at detecting low leakage systems.

An opposite concern, which appeared in the current field data, can happen in leakier duct systems with fan pressurization techniques. If the leakage is too high, it may not be possible to reach the reference pressure (25Pa) and that requires extrapolation to the nominal rating point. This induces an additional source of bias both from the extrapolation and from calibration errors with equipment operating at their extreme limits. As shown in this study, in some cases the results are completely unrealistic.

Time and Cost

The DeltaQ test is the fastest on average – taking 54 minutes on average and about 10 to 15 minutes faster than the two pressurization tests. The variability in time to perform tests for all three procedures was about 20 minutes.

In evaluating costs for testing, it is important to consider what is happening in conjunction with the duct leakage testing. For example, it is quite common to also measure envelope leakage using a blower door so for DeltaQ and leakage to outside testing there may not be an additional cost to set up the blower door. In addition, the DeltaQ test includes an envelope leakage test and thus the marginal costs could be significantly lower than the other two approaches. Detailed discussion of costs is beyond the scope of this report, however.

In terms of time and cost the DeltaQ test has a small advantage over the pressurization tests.

CONCLUSION

Our objective in this report was to determine if the repeatability errors any of the three common duct leakage measurement techniques were sufficiently poor that it should be a-priori eliminated as an option for use. The answer to that question is “no”.

Our field work did show that the duct pressurization to outside test method had superior repeatability over all, but that the other two were acceptable. Each measurement technique had pros and cons depending on the application, the result needed and specific environment. Therefore the results of the current repeatability study combined with other field and laboratory testing indicate that there is no way to a priori eliminate any of these test methods from being used. Selection of the test method to be used should remain flexible with selection based on home and duct characteristics, other testing to be undertaken and the objectives of the testing.

Test Method Selection Guidance

Although there are no conclusions that universally point toward or away from a particular method, we can provide some guidance on situations where one technique may be superior to another. The following recommendations should be considered when determining what methods to use or require:

- If the HVAC system has components (ducts, furnace and/or blower) in a basement or crawlspace then use the DeltaQ test.
- When duct leakage is expected to be small and repeatability is most important use the fan pressurization to outside method.

- When total leakage is expected to be high, do not use the total system leakage method.
- When duct leakage to outside is expected to be high and the data is for energy or IAQ, use the DeltaQ method.
- When on-site costs or time are an issue, use the DeltaQ method. This is especially true if sealing registers may be difficult or if envelope leakage testing is also required.
- If the entity specifying the test has specified one specific metric, use the test that best generates that metric.

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APPENDIX A: FIELD TESTS PROCEDURES

Field Testing Protocol

At each house the following was recorded or measured:

0. Duct system leakage. Total for pressurization and supply, return and total for DeltaQ.

1. Total HVAC system air flow will be measured using the pressure matching technique in ASTM E1554 (and Title 24 and RESNET standards) or The Energy Conservatory flow plate. For HVAC systems that are both heating or cooling, or have variable speed blowers this air flow measurement should be at the highest blower speed.

2. Floor area

3. Number of stories & if single or multifamily

4. Duct location(s)

5. Location - preferably street address, but at least the city/state and/or zipcode.

6. Local weather - temperature and windspeed. Could be either an on-site weather station or closest weather site publically available. Record the temperature and windspeed for each test.

7. Number of supply grilles/registers

8. Number of return grilles/registers

9. Time to perform each test.

10. Date of test.

11. Notes on if the house is new or retrofit, a DOE Challenge Home or Energy Star home (or other program the house may be participating in), if the house was being rated (e.g., using this leakage test for a HERS score).

Pressurization testing

Both the total system leakage test and leakage to outside pressurization tests use the procedures in ASTM E1554 or California Title 24 Reference Appendixes.

After each pressurization test, all the register covers are removed, the duct blaster disconnected and pressure probes removed from the system. This is done to include any repeatability issues stemming from equipment installation.

DeltaQ testing

Automated software was used to perform the testing. The software controls the blower door, records the data and performs all the required calculations (and prompts the user to change blower door orientation, rings, turn HVAC fan on and off). LBNL provided additional guidance for DeltaQ testing, such as placement of tubing, location of the blower door (e.g., if there is an attached garage then the main garage door should be opened and the blower door installed in the doorway between the house and garage) and criteria for redoing parts of the test (the software allows parts of the DeltaQ test to be repeated without redoing the whole test. This is useful if, for example, a tube is stepped on during the test or the blower door/blower door rings are not in the correct orientation).

After each DeltaQ test, the HVAC system was returned to normal operation and the blower door assembly uninstalled. This is done to include any repeatability issues stemming from blower door installation and HVAC system operation.

Appendix B. Data Summaries from Field Testing

CEE - all flows in cfm													Time (minutes)						Number of tests			Wind speed (mph)			Floor Area
		Press		Pout		DeltaQ Supply		DeltaQ Return		DeltaQ Total		HVAC Flow	DeltaQ test 1	DeltaQ other	Press test 1	Press other	Pout test 1	Pout other	DeltaQ	Press	Pout	DeltaQ	Press	Pout	Ft^2
Site	Envelope leakage Q50	avg	sd	avg	sd	avg	sd	avg	sd	avg	sd	avg	avg	avg	avg	avg	avg	avg							
1	1952	817	4	88	0	-10	4	23	6	13	11	745	19	19	45	25	45	42	6	7	10	4	11	9	2552
2	1315	564	8	0	0	11	13	12	9	23	22	704	48	24	76	29	60	37	5	8	5	7	11	8	2042
3	2289	1017	5	49	2	-3	10	1.5	17	-1	25	814	50	18	75	38	65	40	6	7	7	5	13	14	2744
4	945	948	8	38	0	10	9	3	15	13	24	852	48	17	100	37	92	39	9	7	7	7	12	8	1992
5	2032	952	9	88	3	8	19	26	27	34	45	839	48	19	80	25	48	30	7	8	8	8	15	17	1864
6	1487	1447	12	87	1	11	19	20	43	31	62	862	90	18	60	36	54	39	7	8	8	9	15	13	2208
7	1847	621	8	39	1	52	14	18	18	70	31	756	50	17	70	31	65	32	8	8	8	6	5	6	1270
8	1985	1447	16	112	1	22	15	47	17	61	35	965	17	17	85	37	75	39	7	7	7	8	12	13	2554
9	2911	122	3	70	2	44	25	59	21	103	39	944	80	19	80	40	90	42	8	7	8	6	8	12	3576
10	2595	2074	7	298	8	10	27	31	36	41	70	1424	78	18	85	39	80	42	6	7	7	12	8	11	3848
Average	**1936**	**1000.9**	**8**	**86.9**	**1.8**	**15.5**	**15.5**	**24.05**	**20.9**	**38.8**	**36.4**	**890.5**	**52.8**	**18.6**	**75.6**	**33.7**	**67.4**	**38.2**	**6.9**	**7.4**	**7.5**	**7.2**	**11**	**11.1**	**2465**
sdev	**587**	**547.4**	**3.8**	**81.1**	**2.4**	**19.3**	**7.2**	**18.1**	**11.5**	**31.3**	**18.4**	**204.9**	**24.2**	**2.1**	**15.0**	**5.7**	**16.5**	**4.2**	**1.2**	**0.5**	**1.3**	**2.3**	**3.2**	**3.3**	**781.6**

PARR - all flows in cfm													Time (minutes)						Number of tests			Wind speed (mph)			Floor Area
		Press		Pout		DeltaQ Supply		DeltaQ Return		DeltaQ Total		HVAC Flow	DeltaQ test 1	DeltaQ other	Press test 1	Press other	Pout test 1	Pout other	DeltaQ	Press	Pout	DeltaQ	Press	Pout	Ft^2
Site	Envelope leakage Q50	avg	sd	avg	sd	avg	sd	avg	sd	Avg	Sd	avg	avg	avg	avg	avg	avg	avg							
1	3310	1988	113	2408	100	511	38	311	53	831	89	1026	80	31	30	30	60	28	10	8	10	3	3	4	1215
2	1226	440	22	245	12	49	9	14	13	63	20	380	45	35	45	30	45	30	8	8	8	2	3	3	1050
3	2201	158	2	75	2	41	7	39	13	80	18	518	50	31	90	26	90	26	8	8	8	2	2	2	1032
4	2797	1991	87	660	24	123	37	150	74	273	108	1736	50	n/a	90	60	90	60	8	5	5	2	1	1	3136
5	982	227	8	163	6	71	5	91	4	162	8	739	45	30	45	20	45	20	7	10	10	1	3	3	1734
6	1408	242	8	137	3	6	7	4	5	9	12	679	30	30	60	28	60	28	7	10	10	4	1	1	830
7	1920	400	12	333	5	163	11	187	9	350	18	632	60	30	45	20	45	20	7	6	6	1	3	3	800
8	1790	385	6	25	1	70	14	37	17	107	26	2942	70	38	60	18	60	18	6	8	8	3	2	2	1688
9	940	110	3	n/a	n/a	16	6	-4	7	12	12	996	n/a	n/a	30	11	30	10	5	10	9	1	2	2	925
10	3445	714	40	381	12	17	8	-9	17	8	9	650	60	25	105	24	105	24	2	7	8	3	2	2	1230
Ave	**2002**	**66**	**3**	**49**	**1**	**10**	**1**	**82**	**2**	**18**	**3**	**102**	**54.**	**31.**	**60**	**26**	**63**	**26**	**6.8**	**8**	**8.**	**2.2**	**2.**	**2.**	**13**

rage		5.5	0.1	1.9	8.3	6.7	4.2		1.2	9.5	2	9.8	4	25		.7		.4			2		2	3	64
sdev	921	718.5	39.0	743.7	31.5	150.4	12.6	104.6	23.3	253.2	35.7	771.1	14.9	3.8	26.5	13.1	24.3	13.2	2.1	1.7	1.7	1.0	0.8	0.9	701.3

Southface - all flows in cfm																									
													Time (minutes)						Number of tests			Wind speed (mph)			Floor Area
		Press		Pout		DeltaQ Supply		DeltaQ Return		DeltaQ Total		HVAC Flow	DeltaQ test 1	DeltaQ other	Press tests 1	Press other	Pout test 1	Pout other	DeltaQ	Press	Pout	DeltaQ	Press	Pout	Ft^2
Site	Envelope leakage Q50	avg	sd	avg	sd	avg	sd	avg	sd	Avg	sd	avg	avg	avg	avg	avg	avg	avg							
1	4086	384	58	222	8	142	53	136	74	216	165	395	-	-	-	-	-	-	7	7	9	0	1	2	2572
2	3974	1229	87	270	27	89	21	137	35	226	54	1010	-	-	-	-	-	-	8	8	8	1	2	1	2318
3	1804	1503	97	388	10	88	23	22	20	110	43	1128	-	-	-	-	-	-	8	8	8	1	1	1	1678
4	1219	101	5	78	2	20	3	10	6	30	9	900	-	-	-	-	-	-	7	8	11	0	0	0	1052
5	3017	1233	75	400	7	49	19	78	24	124	66	930	-	-	-	-	-	-	7	9	7	2	1	2	-
6	2282	3466	420	1639	62	153	17	274	14	427	28	635	-	-	-	-	-	-	8	8	8	-	-	-	900
7	2180	253	7	216	6	93	19	142	14	236	32	600	-	-	-	-	-	-	7	8	8	1	0.1	1	1723
8	1736	395	81	113	2	45	16	74	17	121	31	728	-	-	-	-	-	-	6	8	8	0.5	0.5	0.1	-
9	4456	1549	69	664	11	209	19	313	38	522	56	296	-	-	-	-	-	-	8	8	8	1.5	1.5	2	1750
10	4032	632	16	432	13	63	23	69	21	130	37	438	-	-	-	-	-	-	6	8	8	1.5	0	1	1267
Average	**2879**	**1074.5**	**91.5**	**442.2**	**14.8**	**95.1**	**21.3**	**125.5**	**26.3**	**214.2**	**52.1**	**706**	-	-	-	-	-	-	**7.2**	**8**	**8.3**	**0.94**	**0.79**	**1.12**	**1657.5**
sdev	**1181**	**996.3**	**120.3**	**454.2**	**18.0**	**57.7**	**12.5**	**99.9**	**19.3**	**152.5**	**42.9**	**281.2**	**-**	**-**	**-**	**-**	**-**	**-**	**0.8**	**0.5**	**1.1**	**0.7**	**0.7**	**0.8**	**582.9**

CEE - all flows in % of blower flow											
		Press		Pout		DeltaQ Supply		DeltaQ Return		DeltaQ Total	
Site	Envelope leakage Q50	avg	sd	avg	sd	avg	sd	avg	sd	avg	sd
1	1952	110	1	12	0	-1	1	3	1	2	1
2	1315	80	1	0	0	2	2	2	1	3	3
3	2289	125	1	6	0	0	1	0	2	0	3
4	945	111	1	4	0	1	1	0	2	2	3
5	2032	113	1	10	0	1	2	3	3	4	5
6	1487	168	1	10	0	1	2	2	5	4	7
7	1847	82	1	5	0	7	2	2	2	9	4
8	1985	150	2	12	0	2	2	5	2	6	4
9	2911	13	0	7	0	5	3	6	2	11	4
10	2595	146	0	21	1	1	2	2	3	3	5
Average	**1936**	**110**	**1**	**9**	**0**	**2**	**2**	**3**	**2**	**4**	**4**

PARR - all flows in % of blower flow											
		Press		Pout		DeltaQ Supply		DeltaQ Return		DeltaQ Total	
Site	Envelope leakage Q50	avg	sd	avg	sd	avg	sd	avg	sd	avg	sd
1	3310	194	11	235	10	50	4	30	5	81	9
2	1226	116	6	64	3	13	2	4	3	17	5
3	2201	31	0	14	0	8	1	8	3	15	3
4	2797	115	5	38	1	7	2	9	4	16	6
5	982	31	1	22	1	10	1	12	1	22	1
6	1408	36	1	20	0	1	1	1	1	1	2
7	1920	63	2	53	1	26	2	30	1	55	3
8	1790	13	0	1	0	2	0	1	1	4	1
9	940	11	0	0	0	2	1	0	1	1	1
10	3445	110	6	59	2	3	1	-1	3	1	1
Average	**2002**	**72**	**3**	**51**	**2**	**12**	**2**	**9**	**2**	**21**	**3**

Southface - all flows in % of blower flow											
		Press		Pout		DeltaQ Supply		DeltaQ Return		DeltaQ Total	
Site	Envelope leakage Q50	avg	sd	avg	sd	avg	sd	avg	sd	avg	sd
1	4086	97	15	56	2	36	13	34	19	55	42
2	3974	122	9	27	3	9	2	14	3	22	5
3	1804	133	9	34	1	8	2	2	2	10	4
4	1219	11	1	9	0	2	0	1	1	3	1
5	3017	133	8	43	1	5	2	8	3	13	7
6	2282	546	66	258	10	24	3	43	2	67	4

7	2180	42	1	36	1	16	3	24	2	39	5
8	1736	54	11	16	0	6	2	10	2	17	4
9	4456	523	23	224	4	71	6	106	13	176	19
10	4032	144	4	99	3	14	5	16	5	30	8
Average	**2879**	**181**	**15**	**80**	**2**	**19**	**4**	**26**	**5**	**43**	**10**